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GSF Focus

The second continent: Existence of granitic continental materials around the bottom of the mantle transition zone

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A B S T R A C T

It has been thought that granitic crust, having been formed on the surface, must have survived through the Earth's evolution because of its buoyancy. At subduction zones continental crust is predominantly created by arc magmatism and is returned to the mantle via sediment subduction, subduction erosion, and continental subduction. Granitic rocks, the major constituent of the continental crust, are lighter than the mantle at depths shallower than 270 km, but we show here, based on first principles calculations, that beneath 270 km they have negative buoyancy compared to the surrounding material in the upper mantle and transition zone, and thus can be subducted in the depth range of 270–660 km. This suggests that there can be two reservoirs of granitic material in the Earth, one on the surface and the other at the base of the mantle transition zone (MTZ). The accumulated volume of subducted granitic material at the base of the MTZ might amount to about six times the present volume of the continental crust. Our calculations also show that the seismic velocities of granitic material in the depth range from 270 to 660 km are faster than those of the surrounding mantle. This could explain the anomalous seismic-wave velocities observed around 660 km depth. The observed seismic scatterers and reported splitting of the 660 km discontinuity could be due to jadeite dissociation, chemical discontinuities between granitic material and the surrounding mantle, or a combination thereof.

1. Introduction

Continental crust has long been considered to be gravitationally stable on the Earth's surface because its density is lower than the underlying mantle. Hence, it was thought that continental crust, once formed, must accumulate on the Earth's surface, following the steady-state accumulation of tonalite-trondhjemite-granodiorite (TTG) magmas produced by plate tectonics. However, in contrast to this traditional view, ubiquitous subduction of TTG crust was proposed by seismological and geological studies of consuming plate boundaries, leading to new concepts of tectonic erosion and arc subduction (von Huene and Scholle, 1991; Yamamoto et al., 2009; Isozaki et al., 2010; Stern, 2011). This suggests that the fate of subducted TTG material and its total amount in the present mantle must be of primary importance of mantle dynamics, because granitic materials include a large amount of radiogenic elements.

Considerations of thermal evolution for the Earth's mantle suggest that intense continental growth must have occurred in the Hadean to Archean, because higher mantle temperatures in the ancient Earth produced extensive amounts of TTG magma (Tatsumi, 1989; Korenaga, 2006). This suggests that a volume amounting to more than 100% of the present continental crust must have been formed on the ancient Earth (Fyfe, 1978). Recent active investigations on the U-Pb and Lu-Hf isotopic systematics of detrital zircon show that the formation of continental crust started 4.4 Ga and that at least 70% of the existing continental crust was produced from the mantle before 2.5 Ga (Harrison, 2009; Belousova et al., 2010).

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However, Archean crust dominates only a small portion (5%–10%) of the Earth's continents, and vestiges of Hadean crust are only preserved in detrital zircons (Harrison, 2009). To explain this discrepancy (called the continental paradox), a means of long term destruction and subduction of Archean TTG has been proposed (Scholl and von Huene, 2007; Shimoda, 2009).

Subduction and recycling of differentiated material into the mantle are of considerable significance not only for continental growth models (Armstrong and Harmon, 1981) but also for creating mantle heterogeneity (Zindler and Hart, 1986). Trace element and isotopic studies of ocean island basalts have pointed out the presence of long-lived (1–2 Ga) recycled components related to ancient oceanic/continental crust stored in the deep mantle (Hofmann, 1997). However, the amount and fate of continental crust subducted into the mantle throughout the Earth's history remain poorly understood.

The traditional geological point of view was that continental crust is not subducted into the deep mantle, due to its buoyancy. However, it has been proven that continental crust (metasediment and tonalitic gneiss) subducted to depths of 150–200 km can later be exhumed to the surface (Chopin, 2003). But if continental materials are subducted to depths greater than 270 km depth they will not return to the Earth's surface because subducted granitic materials are no longer buoyant at depths greater than 270 km, at which coesite, a high pressure polymorph of SiO_2, transforms to stishovite (Irifune et al., 1994). After further subduction, these materials will be buoyant again compared to the surrounding mantle at the base of the MTZ (23.8 GPa), due to the dissociation of ringwoodite to Mg-perovskite and magnesiowustite. Thus subducted granitic material can be expected to be trapped at depths of 660 km (Irifune et al., 1994; Rapp et al., 2008; Wu et al., 2009). To confirm this we conduct first principles studies of the elastic properties expected for granitic materials at depths greater than 270 km, discussed below.

Previous studies (e.g., Anderson and Bass, 1986; Li et al., 1998; Irifune et al., 2008) have suggested that seismic velocities in pyrolite composition measured in laboratory are higher than seismological observations such as PREM (Dziewonski and Anderson, 1981). There has been controversy on what produces the anomalous seismic-wave velocity and density changes observed at depths of around 660 km. Separated oceanic crust has been suggested to be a candidate to explain this anomaly (e.g., Karato, 1997; Fig. 1A). On the other hand, recent experimental (Irifune et al., 2008) and theoretical (Cammarano et al., 2009) studies suggest that the PREM (Dziewonski and Anderson, 1981) velocities are higher than those of adiabatic pyrolite (Ringwood, 1975) in the lower part of the MTZ and that either subadiabatic temperatures of 400 K or seismically faster chemical composition such as harzburgite is required to explain the velocity difference (Irifune et al., 2008; Fig. 1B). However, it is unlikely that a temperature decrease of 400 K occurs in this depth range throughout the entire mantle. Also, light harzburgite could be gravitationally unstable. Moreover, the fast PREM velocities in the uppermost lower mantle cannot be explained even by the most depleted composition, harzburgite (Cammarano et al., 2009).

As none of the above possibilities seemed acceptable, we proposed a new model: TTG-enriched material in the mantle transition zone (Kawai et al., 2009; Fig. 1C). Here we examine whether subducted granitic material could produce the anomalous velocity and density discrepancies observed in the lowermost MTZ and the uppermost lower mantle. To our knowledge, this possibility has not previously been considered, probably because theoretical results on the elastic properties of granitic materials were not previously available.

2. Methods and results

We calculate the density and elasticity of TTG crust by means of *ab initio* density functional computation methods. Archean TTG is low on potassium feldspar (Martin et al., 2005). Here, we assume a hypothetical TTG crust, whose mineral proportion has the molar fraction albite:quartz is 1:7 (Komabayashi et al., 2009). Albite dissociates into quartz and jadeite at 2–3 GPa (at 70–100 km depth) and 1300 K (Birch and LeComte, 1960) and jadeite then further dissociates into an assemblage of stishovite and calcium ferrite (CF)-type phase at about 23 GPa (at 640 km depth) and 1300–1500 K (Yagi et al., 1994; Kawai and Tsuchiya, 2010). SiO_2 polymorph undergoes a phase transition from quartz to coesite at 70–100 km depth and from coesite to stishovite at depths of 250–300 km. The approximate mineral proportion of TTG has the molar fraction jadeite:stishovite is 1:8 after the coesite-stishovite transition and CF:stishovite is 1:9 after jadeite dissociation. In this study we compute the density and seismic velocities, v_P and v_S, of TTG assemblage in the pressure range between 10 and 50 GPa, taking the Voigt-Reuss-Hill averages of elastic constants for jadeite, a CF-type phase and stishovite, which have recently been calculated based on first principles (Kawai and Tsuchiya, 2010). Our calculations show that increases of the density and P and S velocities associated with the jadeite dissociation at a pressure of about 23 GPa are 4.4%, 6.1%, and 8.1%, respectively (Fig. 2).

The major component in pyrolite composition is wadsleyite in the 15–20 GPa pressure range and ringwoodite in the 20–23.5 GPa range; it dissociates into perovskite (pv) and ferropericlase (fp) at about 23.5 GPa. In this study, we approximate pyrolite as forsterite

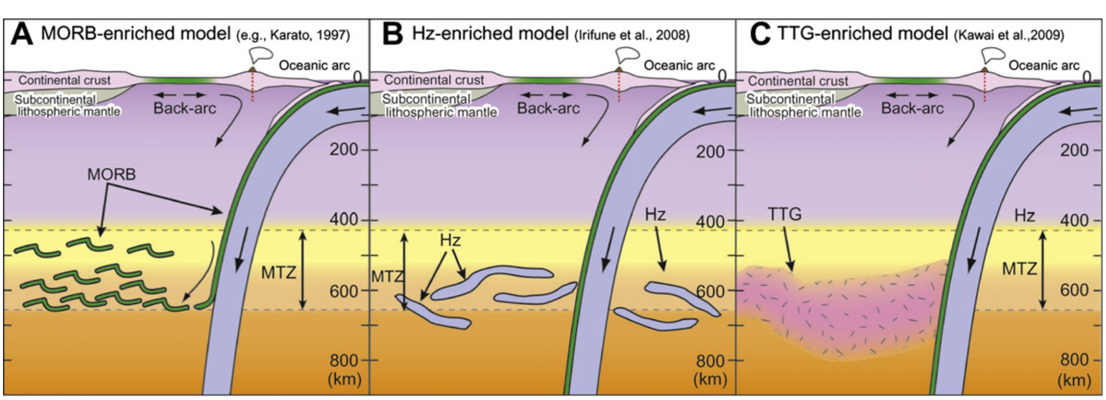

Figure 1. Models to explain the velocity anomaly in the MTZ (410–660 km depth range). A: MORB-enriched model (e.g., Karato, 1997) due to segregation of the MORB crust at the MTZ; B: Harzburgite (slab-restite)-enriched model by Irifune et al. (2008); C: TTG-enriched model (Kawai et al., 2009).

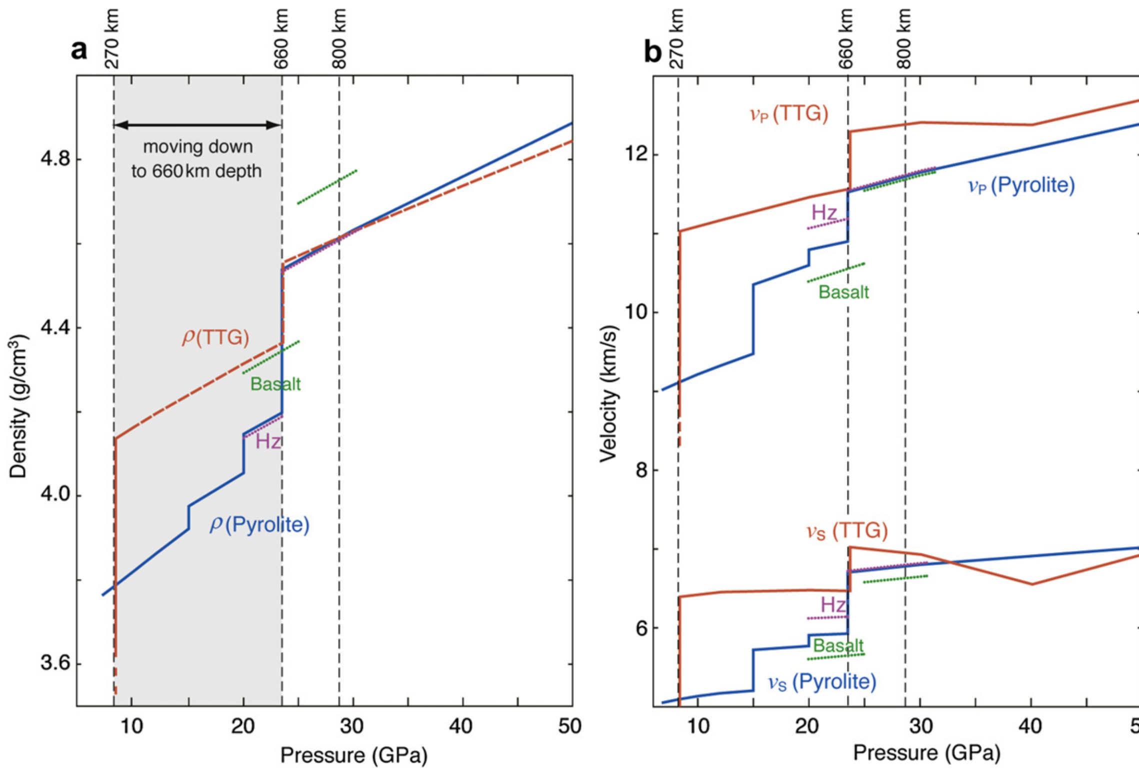

Figure 2. Depth-dependence of density (a) and seismic velocities (b) of pyrolite composition (pyrolite; blue) and TTG (red) as well as harzburgite (Hz; purple) and basalt (green) around depths of 660 km. In the depth range from 270 to 800 km the velocities of TTG are faster than those of pyrolite composition, and TTG is denser than pyrolite composition (and will move downward if it exists at 270 km depth). Thus the anomalous seismic velocities of one-dimensional models such as PREM and AK135 (Dziewonski and Anderson, 1981; Kennett et al., 1995) around depths of 660 km could be due to granitic materials. In contrast, other assumed compositions such as basalt and harzburgite do not have both higher velocities and density than pyrolite composition.

containing 10 mol% of Fe (Tsuchiya and Tsuchiya, 2006). The impurity effects of iron are taken into account using results of Tsuchiya and Tsuchiya (2006). We use 0.3 as the partition coefficient between pv and fp (i.e. pv and fp include 5 mol% and 15 mol% of Fe, respectively). We use published elastic properties for forsterite (da Silva et al., 1997), wadsleyite (Kiefer et al., 2001), ringwoodite (Kiefer et al., 1997), and perovskite (Tsuchiya et al., 2004). Taking the average, we obtain the density and seismic velocities of pyrolite composition. The seismic velocity increases associated with the wadsleyite-ringwoodite (520 km) and post-spinel (660 km) phase transitions are 1.9% and 5.9% for P-velocity, and 2.4% and 13.2% for S-velocity, respectively (Fig. 2).

We compute density and elastic properties of harzburgite and basalt around depths of 660 km. The mineral proportion of harzburgite has the volumetric fraction ringwoodite:majorite of 90:10, while that of basalt is majorite:stishovite of 90:10 above the 660 km depth. We use published elastic properties for ringwoodite (Kiefer et al., 1997), majorite (Irifune et al., 2008), Ca-perovskite (Tsuchiya, 2011), and stishovite (Kawai and Tsuchiya, 2010).

We consider the density and elastic properties expected for granitic materials at depths below 270 km using *ab initio* density functional computation methods. We compute the density and seismic-wave velocities, v_P and v_S, of a TTG assemblage in the pressure range between 10 and 50 GPa and compare the density and seismic velocities of TTG to those of pyrolite composition (Fig. 2). Note that although density and elastic constants are computed at the static temperature, the phase transition pressures are corrected along the normal geotherm (Brown and Shankland, 1981). Due to the coesite-stishovite phase transition at the depth of 270 km, TTG is denser than the surrounding mantle materials in the MTZ, but is lighter than mantle materials at depths greater than about 660 km. Note that due to simplification of the TTG composition, the subtle density difference between the TTG and pyrolite composition between 660 and 800 km depths is neglected. The above calculations confirm that TTG will be negatively buoyant relative to pyrolytic material at a depth of 270 km, suggesting that TTG could be gravitationally trapped around 660 km depth (Fig. 2).

We next compare the seismic velocities of TTG to those of pyrolite composition. Our calculations show a large velocity increase associated with the jadeite dissociation to calcium ferrite (CF)-type phase and stishovite at a pressure of about 23 GPa. The P and S wave velocities of TTG are respectively 8.2% and 12.3% faster than those of pyrolite composition in the pressure range from 15 to 20 GPa and respectively 5.0% and 1.8% faster in the range from 20 to 23.5 GPa. If TTG is stagnant at a pressure of 28 GPa, the boundary between TTG and pyrolite composition will produce 6.2% and 4.4% velocity decreases for P and S waves, respectively (Fig. 2).

3. Discussion

We simplified the compositions of both TTG and pyrolite composition, neglecting the effects of thermal expansion because the calculations were for static conditions, but this does not affect the conclusion that TTG is denser than pyrolite composition in the depth range from 270 to 660 km, suggesting that if TTG is carried to depths of 270 km by being entangled with a subducted slab, it then will apply a negative buoyant force to the subducted slab. Also, as the subducted slab becomes cold relative to the surrounding mantle (e.g., a slab temperature of about 1500 K at a depth of 660 km), TTG will become much denser due to the dissociation of jadeite at a depth of 640 km and will apply a larger negative buoyant force, resulting in TTG accumulating at the base of the MTZ.

It is well known that the seismological models have anomalously fast velocities at the bottom of the MTZ. This means that in the lowermost MTZ materials which are gravitationally trapped and have faster seismic velocities than the surrounding mantle are required. Harzburgite has faster seismic velocities but is gravitationally unstable, while basalt is gravitationally stable but has slower velocities in this depth range. In the uppermost lower mantle, meanwhile, harzburgite is stable in the limited depth range from about 660 to 700 km, but seismic velocities such as those of PREM are too fast to be explained by harzburgite in this depth range (Cammarano et al., 2009). On the other hand, we showed above that granitic materials are both gravitationally stable and can produce high seismic wave velocities at these depths. In order to roughly estimate the proportion of granitic materials in the MTZ, we compare the P and S wave velocities obtained by Irifune et al. (2008) to PREM. We cannot directly compare velocities in seismological models to those calculated in this study, because our calculations were conducted at the static temperature. Therefore, we use relative velocity differences between a TTG assemblage and pyrolite composition and between the PREM and results measured by Irifune et al. (2008). The discrepancy of velocities between PREM and the results of Irifune et al. (2008) can be explained by an assemblage of 25 vol.% and 75 vol.% of the TTG and pyrolite composition, respectively (Fig. 3). If TTG accumulated in the depth range between 520 and 660 km, the volume of TTG of $\sim 1.5 \times 10^{10}$ km^3 would be thus about six times the present volume of the upper and middle crust (about three times the present volume of continental crust) on the Earth's surface, considering its thermal expansion.

The volume of granitic material in the MTZ obtained from our calculations is large but it is not surprising in consideration of the modern subduction flux of continental debris via subduction zones. At modern subduction zones, processes of sediment subduction and subduction erosion transport continental material toward the deep mantle with a solid-volume rate of 2.5–3.7 km^3/yr (Scholl and von Huene, 2007; Clift et al., 2009). Using this removal rate, a volume of continental material of $\sim 7 \times 10^9$ km^3 could have been removed from the Earth's surface during the past 1.9–2.8 Ga. Assuming recycling of continental crust from the early Archean to the present, the volume of continental crust recycled into the deep mantle could be several times larger than the present volume of continental crust.

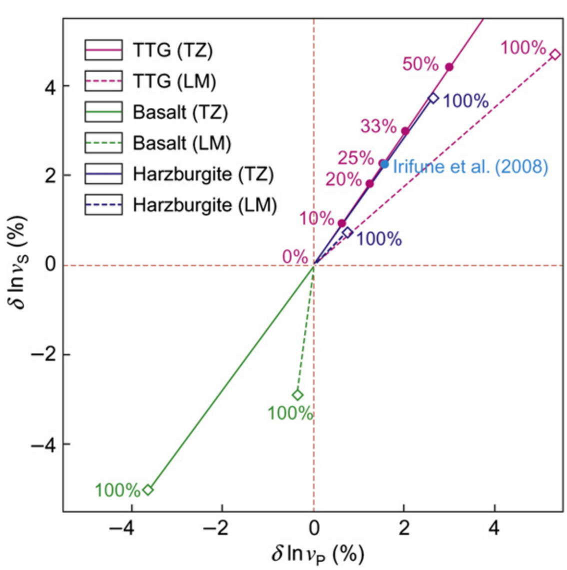

Figure 3. Difference of P and S wave velocities from the mantle average composition in the depth range from 520 to 660 km (TZ; solid line) and from 660 to 800 km (LM; dotted line). Differences of TTG (red), harzburgite (purple) and basalt (green) are shown. The red dots indicate the vol.% of TTG. The blue dot indicates the difference between the experimental results of Irifune et al. (2008) and the PREM model (Dziewonski and Anderson, 1981). The velocity difference at the bottom of MTZ can be explained by 25 vol.% of TTG. Harzburgite produces faster velocities than pyrolite composition but is lighter in composition and is thus gravitationally unstable. Majorite-rich basalt is denser than pyrolite composition but produces slower velocities (Irifune et al., 2008). On the other hand, while harzburgite produces little velocity difference and basalt has slower velocity in the uppermost lower mantle, TTG can produce higher velocity than the surrounding mantle. Granitic material is thus the only known acceptable candidate which is both gravitationally stable and produces faster velocities around depths of 660 km.

In this study, the mineral proportions in hypothetical TTG are approximated in molar fraction as an albite:quartz ratio of 1:7. However, natural TTG and terrigenous sediment, which are subducted into the mantle, contain other elements such as potassium and calcium. In the pressure range of the MTZ, potassium and calcium mainly form K-hollandite and grossular garnet, respectively (Irifune et al., 1994; Wu et al., 2009). Since the densities and velocities of these minerals are higher than those of jadeite but they do not undergo phase transitions in this pressure range (Stixrude and Lithgow-Bertelloni, 2005; Mookherjee and Steinle-Neumann, 2009), the presence of such minerals would produce a small baseline shift. Thus our estimate of the amount of granitic material in the MTZ is subject to some uncertainty, but the basic conclusion that granitic materials are gravitationally trapped in the lowermost MTZ and the uppermost lower mantle (in contrast to harzburgite) and can explain the seismic velocity anomaly better than other proposed candidate compositions is not affected.

The depth at which the post-spinel phase transition occurs is close to the depth at which jadeite dissociates to a CF-type phase at a typical adiabatic temperature of 1800 K in the MTZ. While the post-spinel phase transition has a negative Clapeyron slope, the jadeite dissociation has a positive slope. Along a cold slab temperature profile, the depths at these phase transitions occur will differ from one another (Fig. 4). As the subduction zone is colder than the surrounding mantle, it is possible that the depths of the respective discontinuities might be far enough apart enough to

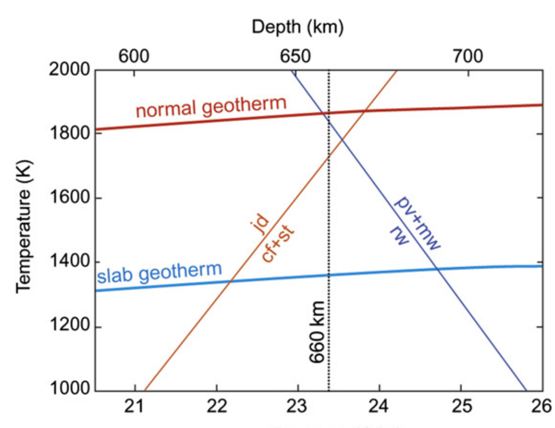

Figure 4. Phase boundaries of post-spinel and post-jadeite transitions with Clapeyron slopes of −2.9 and +2.8 MPa/K for post-spinel (Yu et al., 2007) and post-jadeite (Kawai and Tsuchiya, 2012) and the mantle geotherm (Brown and Shankland, 1981) (jd = jadeite; cf = CF-type phase; st = stishovite; rw = ringwoodite; pv = magnesium perovskite; mw = magnesiowüstite). The decompositions of both ringwoodite and jadeite occur at almost the same depth (about 660 km) at the normal geotherm temperature of 1800 K, but a slab 500 K colder than the normal mantle can yield a 70 km depth separation between the two decompositions, which could produce splitting of the seismic 660 km discontinuity (Simmons and Gurrola, 2000; Deuss and Woodhouse, 2001). The anomalous seismic velocity of one-dimensional models such as PREM and AK135 (Dziewonski and Anderson, 1981; Kennett et al., 1995) around 660 km depth could thus be due to granitic materials.

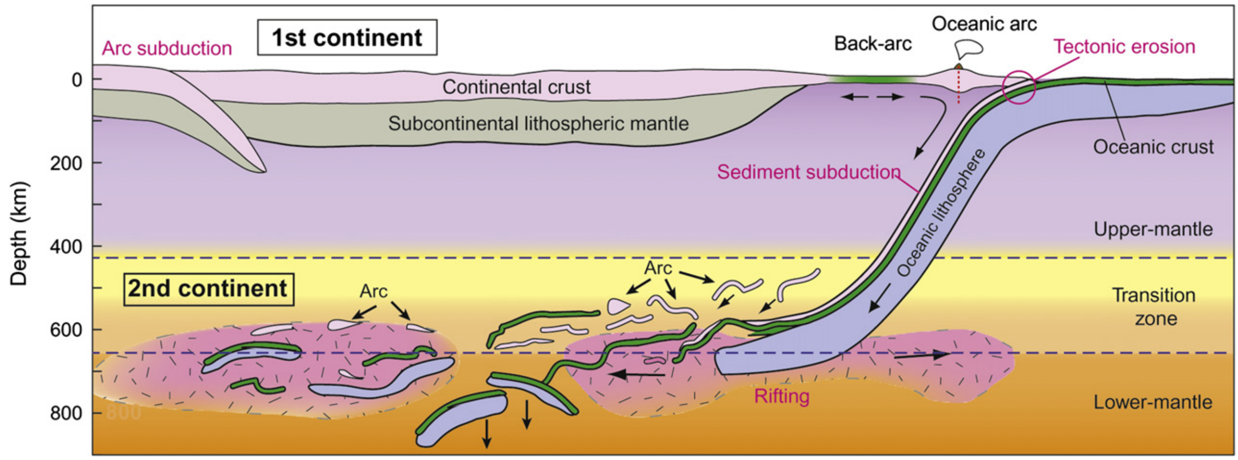

Figure 5. Schematic image of the subduction system in the crust, upper mantle, mantle transition zone, and lower mantle. Depleted oceanic lithosphere (light blue), basaltic oceanic crust (deep green), and granitic material (pink) make up the subducting slab. Granitic materials have been entangled by the slab subduction through sediment subduction, arc subduction, and tectonic erosion. Subducted Archean TTG crust has accumulated at the bottom of the mantle transition zone and a graveyard of granitic material has been formed around 660 km depth. Even if TTG materials are dragged into the lower mantle, they will float up to the gravitationally stable region around 660 km depth over geologic time. The spatial distribution of the graveyard of granitic material could be related to the subduction history, i.e. the aggregation and dispersal of supercontinents. The distribution of granitic materials will determine whether a subducting slab penetrates into the lower mantle or stagnates, because granitic material will interfere with subduction into the lower mantle. The modern granitic continental crust, which is also denser than the mantle materials in the mantle transition zone, will accumulate around 660 km depth, although its mineral proportion will differ slightly from that of TTG. The seismic velocities of granitic materials are faster than those of the surrounding mantle around the 660 km depth. Small amounts of granitic materials are observed as seismic scatterers in the transition zone and in the uppermost lower mantle (Kaneshima, 2009), while a larger scale granite zone could be observed as a faster region in tomographic studies.

be seismically observable. Splitting of the 660 km discontinuity reported beneath the circum-Pacific (Simmons and Gurrola, 2000; Deuss and Woodhouse, 2001) might thus be related to the subduction of continental crust.

While subducted oceanic crust becomes denser than mantle materials in the lower mantle, TTG has lower density at depths greater than 800 km. Thus, if TTG sinks deeper into the lower mantle but then peels off from the subducting slab, it will rise up back to the MTZ due to buoyancy (Fig. 5). Recent seismological studies have found seismic scatterers in the uppermost lower mantle (Kaneshima, 2009) with a strong concentration observed adjacent to a high velocity region interpreted as a stagnant slab at a depth of 800 km beneath southwest Japan (Niu et al., 2005). These can be interpreted as jadeite dissociation and/or a chemical boundary between TTG and the mantle, which produces large velocity jumps (Fig. 5).

Seismic tomography shows a large volume of high velocity regions in the MTZ and even in the uppermost lower mantle (e.g., beneath Japan) (Obayashi et al., 2009). If subducted slabs are stagnant for a long time in the MTZ, they will be warmed and their seismic velocities will become close to those of the surrounding mantle. Hence, the large volume of high velocity regions in and below the MTZ could consist of both subducted slab and granitic mineral (Fig. 5).

4. Conclusion

We have studied density and elasticity of the TTG and pyrolite compositions in the pressure range between 10 and 50 GPa at the static temperature using *ab initio* density functional computation methods and have found that granitic rocks are lighter than the mantle at depths shallower than 270 km and that beneath 270 km they are denser than the surrounding material in the upper mantle and MTZ and can move down to the bottom of the MTZ if they exist at 270 km depth. This suggests that there are two reservoirs of granitic continental material in the Earth: one on the Earth's surface (which we call 'the first continents') and the other at the bottom of the MTZ (called 'the second continents'). The accumulated volume of subducted granitic material at the base of the MTZ might amount to about six times the present volume of the continental crust. Our calculations show that the seismic velocities in stishovite-rich granitic materials in the depth range from 270 to 660 km are faster than those of the surrounding mantle. This could explain seismological observations such as the high velocity anomaly observed around 660 km depth and complexity of 660 km discontinuities. The existence of granitic material including radioactive and incompatible elements at the base of the MTZ could influence both dynamic and chemical evolutions of the Earth through the geological time. Plate tectonics makes the distribution of heat sources in the mantle spatially heterogeneous via production and consumption of granitic material at convergent plate boundaries.

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